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POSSIBLE FERMI MECHANISM OF SOLAR COSMIC RAYS

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Pulsations in solar radio bursts suggest Fermi acceleration of particles trapped in solar magnetic loop. Simple model indicates acceleration of thermal protons to subrelativistic energies within a few seconds.

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1. INTRODUCTION

Of the remarkable series of events in August 1972 documented by Coffey (1973) we may single out the proton event of 4 August. Energetic protons ejected from the sun on the occasion of a solar flare may be divided into three energy groups: those in the Kev, Mev and Gev ranges. To these three groups respectively are attributed the geophysical effects, geomagnetic storm, polar cap absorption (PCA), and ground level event (GLE).

The mechanisms that have been postulated for the acceleration of relativistic galactic cosmic rays involve magnetic fields, the betatron mechanism (Swann, 1933) and moving magnetic mirrors (Fermi, 1949, 1954). Applications have been made to solar conditions. Acceleration mechanisms may vary from flare to flare. The event of 4 August 1972 is an example where the mechanisms varied even within the same event (Levy et al., 1976). While the typical GLE occurs within minutes of the associated solar flares, the GLE of 4 August occurred about seven hours after the associated solar flare. Levy and his group explain the delay by a Fermi mechanism in the interplanetary space between the sun and the earth. The input of this mechanism were particles accelerated in the vicinity of the flare region. Various Fermi mechanisms for the acceleration of solar cosmic rays in the vicinity of the flare region have been proposed by Parker (1957, 1958), Wentzel (1963, 1964) and others. However, the particular model to be explored in this study is that suggested by McLean et al. (1971).

2. ACCELERATION IN A MAGNETIC TRAP

The Fermi mechanism depends on the constancy of the magnetic moment and on moving magnetic mirrors. A particle gains energy after a head-on collision with a moving massive body. For a given situation one then has to identify which will function as moving magnetic mirrors, and then determine quantitative relations. Trapping of charged particles is possible on the sun, for the magnetic field in the vicinity of sunspots of opposite polarity may be described by a dipole field. Consider a short bar magnet buried in the photosphere. Let the polar coordinates r and θ with origin at the center of the magnet specify the field point P(r, θ). Then the components of the field intensity are:

$$B_r = -2M \sin \theta / r^3 \qquad \text{and} \qquad B_\theta = M \cos \theta / r^3$$

The magnitude then of the magnetic field at r, θ is

$$B = M(4 - 3\cos^2\theta)^{1/2}/r^3.$$

The magnetic field is proportional to M and inversely proportional to the cube of the distance from the center of the dipole. Mirroring occurs when a charged particle moves from a region of weak magnetic strength to a region where the field is greater. In a dipolar field a charged particle is trapped between two mirrors. Moreover the charged particles may gain energy if the mirrors are moving.

In Figure 1 is shown a model of how this may happen. A flare occurs in the chromosphere in the vicinity of a magnetic dipolar field. Electromagnetic waves escape. Some energetic particles escape, some fall back to the sun, and others are trapped in the magnetic loop. The trapped particles may gain energy if a plasma cloud moves upward from the sun. For our model, conditions allow the formation of a shock front in the plasma cloud that extends over both legs of the loop. Where the shock front AA' encounters the magnetic loop, the magnetic field is compressed and intensified. We have moving magnetic mirrors. Thus charged particles will be reflected and accelerated on encountering the shock front which is moving with velocity V. The conditions for Fermi acceleration are present.

After some time the shock front will have moved to some position BB' such that the shock front is aligned nearly parallel to the magnetic loop over a length which is large compared to the diameter of the loop tube. Under these conditions the intensity of the synchrotron radiation is modulated by sharp pulses of short period. After the shock front has cleared the loop, the energetic electrons are gradually lost and the pulses die down. Then the continuum radiation decays. Such is the theory worked out by McLean and his group to explain the observations of the radio flare of 27 September 1969. The process that accelerates electrons should also accelerate protons. They found that this and some other events with this peculiar radio signature had an associated proton event.

The 3B flare of 4 August 1972 had an associated radio event that fits the description above. It is described elsewhere (Badillo, 1973). The event was observed at six discrete frequency bands, namely 8800, 4995, 2695, 1415, 606 and 245 MHz. The first four highest frequencies show two broad maxima but the second maximum of the 1415 MHz bursts presents a distinctive pulsation lasting about three minutes. At least 40 spikes were counted in that period.

Now to work out the model for the acceleration of protons in the magnetic loop. A proton with the proper pitch angle, the angle between the velocity vector and the magnetic induction vector, gains energy after a head-on collision with the upward moving shock front at M. Then it is guided by the magnetic lines to a head-on collision with the shock front at m. The proper pitch angle is maintained by scattering at the discontinuity due to the shock front. This allows continued acceleration.

In Figure 2 is shown an equivalent acceleration cell which may be used to calculate the energy gained after n head-on collisions. Consider two parallel plane walls M and m, moving toward each other with velocities whose magnitude is equal to V, a constant. A particle moving with velocity v_o is normally incident on the moving wall M, and bounces in the opposite direction with velocity v_1 after an increase in velocity 2V. After a head-on collision with wall m, it gains another increase in velocity of 2V, and now moves with velocity v_2, and so on. We now have to determine the gain in energy after n head-on collisions.

Let the particle hit wall M at the instant when the distance between walls M and m is L_o. It will meet wall m after time t_1 at which time the wall m has moved a distance Vt_1. The following relations thus hold:

$$v_1 = v_o + 2V$$

$$L_o = t_1(v_1 + V)$$

$$\begin{aligned} L_1 &= L_o - 2Vt_1 \\ &= L_o(v_o + V)/(v_o + 3V) \end{aligned}$$

After colliding with wall m, the particle will meet wall M after time t_2 and the following relations hold:

$$v_2 = v_1 + 2V$$

$$L_1 = t_2(v_2 + V)$$

$$\begin{aligned} L_2 &= L_1 - 2Vt_2 \\ &= L_o(v_o + V)/(v_o + 5V) \end{aligned}$$

From the above considerations we can determine the distance between the walls after n collisions to be

$$L_n = \frac{L_o(v_o + V)}{v_o + (2n + 1)V}$$

Having obtained this, we can now use the relation derived by Spitzer (1962)

$$E_n = E_o(L_o/L_n)^2 \qquad (1)$$

It is also desirable to determine the total elapsed time after n collisions. From Figure 2 we can determine the following relations

$$L_1 = L_2 + 2Vt_2$$

$$L_o = L_1 + 2Vt_1$$

$$= L_2 + 2V(t_1 + t_2)$$

This can be generalized to the following

$$L_o = L_n + 2V(t_1 + t_2 + \ . \ . \ . + t_n)$$

$$= L_n + 2VT$$

where T is the total elapsed time. From this and Equation 1 we can solve for T and we get

$$2VT = L_o \left[1 - (E_o/E_n)^{1/2} \right]$$

With these relations we can work out some numerical problems. In Table 1 are listed some results using representative initial values. The results will enable us to develop a feel for the situation. Two shock front velocities are used: one greater than the escape velocity of 617 km/sec and one less than that. We are interested in the energetic protons that reach the earth in about thirty minutes and thus E_n is determined to be 60 Mev. The initial energy E_o ranges from thermal energies to 100 Kev. The height of the 1415 MHz layer is about 8000 km above the photosphere. The path length of a magnetic line of force of a dipole is hard to integrate exactly so we approximate it to the path length of a circle tangent to the center of the dipole. If the shock front starts 2000 km above the photosphere, then L_o is about 18,000 km.

Table 1

	V=700 km/sec	V=70 km/sec
E_o (ev)	T(sec)	T(sec)
10^5	12.33	123.3
10^3	12.80	128.0
10^1	12.85	128.5
10^{-1}	12.85	128.5

From Table 1 we see that over several magnitudes of the initial energy, the total elapsed time does not vary much for a given V. The time is sensitive to the ratio L_o/V. In the model, the Fermi mechanism is able in a matter of seconds to accelerate thermal protons to subrelativistic energies. In the 4 August 1972 event, these were accelerated to relativistic energies by the mechanism postulated by Levy et al. (1976). This mechanism is quite efficient since all collisions with the moving mirrors are head-on collisions.

3. CONCLUSIONS

This paper attempted to develop a mechanism to explain subrelativistic protons. The model arose from the attempt to explain rapid pulsations in the low frequency (606 and 1415 MHz) radio bursts but not in the higher frequency radio bursts. What was postulated is a type of Fermi mechanism, that is, acceleration in a magnetic trap made possible by the magnetic loop of a dipole field. Calculations indicate that thermal protons can be accelerated to subrelativistic energies in a few seconds. The model developed is a simple one and optimal conditions have been assumed. Further problems to work out are: particle distributions, proton energy spectra, and loss mechanisms.

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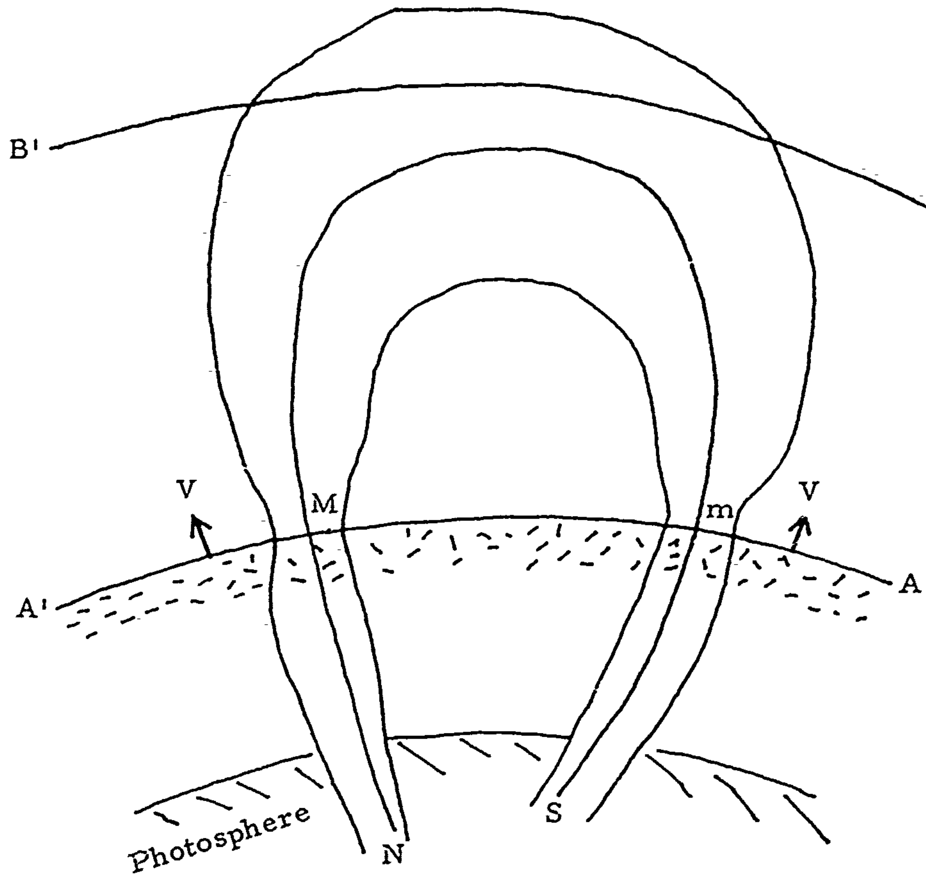

Figure 1. Fermi acceleration in magnetic loop

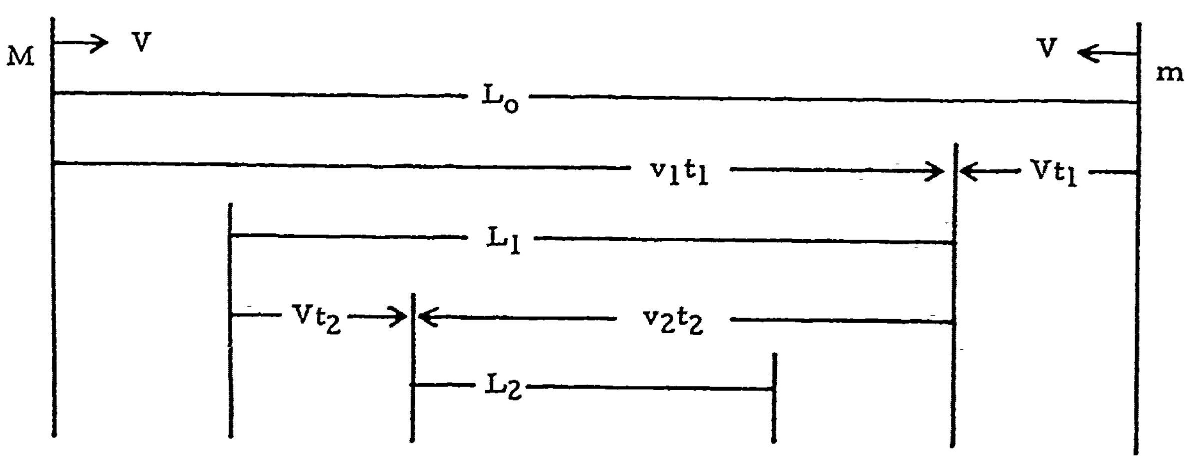

Figure 2. Equivalent acceleration cell